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COMPRESSIVE SENSING AND CODING FOR COMPLEX NETWORKS

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University of Illinois

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Final Report

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14. ABSTRACT

The focus of the research project was on developing an interdisciplinary, analytical approach to dimensionality reduction, information dissemination, aggregation and monitoring over complex networks. In the course of the project's development, the following system solutions were proposed, analyzed and implemented:
1) A novel approach to combating physical and network layer communication errors through the novel framework of network coding, termed Hybrid Network Coding.
2) An algorithmic solution for compressive sensing with side information, termed Sparsely Corrupted Information Bottleneck.
3) A family of distributed vote (ordinal data) aggregation methods over networks, with applications in social choice theory and bioinformatics.

15. SUBJECT TERMS

Compressive Sensing, Matrix Rank Approximation, Network Coding, Social Network Information Aggregation

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FA9550-09-1-0612, 09NL197

1. **Final Report Summary**: The focus of the research project was on developing an interdisciplinary, analytical approach to dimensionality reduction, information dissemination, aggregation and monitoring over complex networks. In the course of the project's development, the following system solutions were proposed, analyzed and implemented:

   a. A novel approach to combating physical and network layer communication errors through the novel framework of network coding, termed Hybrid Network Coding.
   b. An algorithmic solution for compressive sensing with side information, termed Sparsely Corrupted Information Bottleneck.
   c. A family of distributed vote (ordinal data) aggregation methods over networks, with applications in social choice theory and bioinformatics.

2. Accomplishments/New Findings: Describe research highlights, their significance to the field, their relationship to the original goals, their relevance to the AF's mission, and their potential applications to AF and civilian technology challenges.

3. **Personnel Supported:** Professional personnel included

   a. Faculty: Olgica Milenkovic and Angelia Nedich
   b. Post-Docs: Vitaly Skachek and Behrouz Touri.
   c. Students: Amin Emad and Farzad Farnoud

4. **Publications:** All publications are available online, as submitted to the arxive or published in corresponding journal. Conference papers are not listed.

1) A. Emad and O. Milenkovic, “Semi-Quantitative Group Testing: a General Paradigm with Applications in Genotyping,” submitted, 2012 (preliminary papers ITW 2011, ISIT 2012).
2) F. Farnoud, Behrouz Touri, and O. Milenkovic, “A Novel Distance-Based Approach to Constrained Rank Aggregation,” submitted, 2012 (preliminary papers: CDC 2012, SPCOM 2012).
3) F. Farnoud, V. Skachek and O. Milenkovic, “Error-Correction in Flash Memories via Codes in the Ulam Metric,” to appear, IEEE Transactions on Inform. Theory, 2013. 33. V. Skachek, O. Milenkovic and A. Nedich, “Hybrid Noncoherent Network Coding,” to appear, IEEE Transactions on Inform. Theory, 2013.
4) W. Dai, O. Milenkovic, and H. V. Pham, “Structured Sublinear Compressive Sensing via Belief Propagation,” Physical Communication, Special Issue on compressive sensing in communications, vol. 5, no. 2, pp. 76-90, November 2011 (online), June 2012.
5) F. Farnoud and O.Milenkovic,”Sorting Permutations by Cost-Constrained Transpositions,”IEEE Transactions on Information Theory, 58(1): 3-23, 2012.
6) W. Dai, E. Kerman, and O. Milenkovic, ”A Geometric Approach to Low-Rank Matrix Completion,” IEEE Transactions on Information Theory, 58(1): 237-247, 2012.
7) W. Dai, O. Milenkovic, and E. Kerman, ”Subspace Evolution and Transfer (SET) for Low-Rank Matrix Completion,” IEEE Transactions on Signal Processing, 59(7): 3120-3132, 2011.

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5. **Interactions/Transitions:**

Participation/presentations at meetings, conferences, seminars. Both PI actively participated in a number of meeting and conferences, to name a few - ISIT (2009-2012), CDC (2009-2012), ITW (2009-2010) etc. Furthermore, PI Milenkovic is currently serving as TPC Chair for the ISIT 2014 Symposium. Throughout the duration of the grant, she also served as Guest Editor in Chief of the Transactions on Information Theory, and Associate Editor of the Transactions on Communications, Transactions on Signal Processing and Transactions on Information Theory.

6. **Honors/Awards:** PI Milenkovic was elected Senior Member of the IEEE in 2012/2013, and Center for Advanced Studies Associate at University of Illinois in 2012. She is also a co-recipient of the best paper award at the International Symposium on Information Theory, ISIT 2010. Both PI Milenkovic and PI Nedich were recently named Willett scholars at the University of Illinois.

7. New discoveries: The discoveries fall into three main categories --

a) **Compressive sensing and low-rank matrix completion:** We developed three novel methods for dimensionality reduction based on codes on graphs and optimization techniques over Grassman manifolds. In particular, we developed the Subspace Evolution and Transfer (SET) algorithm which operates with high accuracy in the highly subsampled observation domain.
b) **Network Coding:** We developed a generalization of Kotter-Kschischang subspace codes for non-coherent networks, suitable for use when the network introduces both dimension and symbol errors. We showed that when the network introduces a large number of symbol errors, the new family of codes outperforms their subspace code counterparts. Two upper bounds on the size of the proposed codes were derived. These bounds represent a variation of Singleton and of a sphere-packing bounds, respectively. The PIs also showed that a simple concatenated scheme that represents a combination of subspace codes and Reed-Solomon codes, is asymptotically optimal with respect to the Singleton bound. In addition, the PIs also derived two efficient decoding algorithms for concatenated subspace codes. The hybrid network coding scheme was shown to have strong duality relationships with the problem of matrix rank minimization.
c) **Social Choice Theory and Social Networks:** We revisited a classical problem in choice theory – vote aggregation – using novel distance measures between permutations that arise in several practical applications. The distance measures were derived through an axiomatic approach, taking into account various issues arising in voting with side constraints. The side constraints of interest include non-uniform relevance of the top and the bottom of rankings (or equivalently, eliminating negative outliers in votes) and similarities between candidates (or equivalently, introducing diversity in the voting process). The proposed distance functions may be seen as weighted versions of the Kendall distance and weighted versions of the Cayley distance. In addition to proposing the distance measures and providing the theoretical underpinnings for their applications, we also considered algorithmic aspects associated with distance-based aggregation processes. We focused on two methods. One method was based on approximating weighted distance measures by a generalized version of Spearman's footrule distance, and it was shown to have

provable constant approximation guarantees. The second class of algorithms was based on a non-uniform Markov chain method inspired by PageRank, for which currently only heuristic guarantees are known. We extended these results to voting scenarios where one has to take into account the dynamic and volatility of a social network, distributed information choices, and potential changes in votes induced by factors external to the network.